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A Self-Deploying, Depth-Adaptive Coastal Oceanographic Mooring

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A compact, low-cost, self-deploying moored oceanographic sensor system has been developed jointly by the Naval Research Laboratory and the Woods Hole Oceanographic Institution. Called XMOOR (for Expendable Oceanographic Mooring), the system is suitable for a variety of meteorological and oceanographic sensors, may be deployed (and if desired, retrieved) in a matter of minutes by untrained personnel, and automatically adapts the length of deployed line to the water depth, so depth need not be accurately known. A two-way radio link with the user allows both real-time reception of data and transmission of command and control messages to the unit. An ARGOS satellite link allows monitoring of instrument position and selected summary data on the status of sensors and battery power. The system is suitable for both research and operational purposes. This report describes the design of the system and results of initial tests.

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EXECUTIVE SUMMARY

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A SELF-DEPLOYING, DEPTH-ADAPTIVE COASTAL OCEANOGRAPHIC MOORING

1.0 INTRODUCTION

It is well known that oceanographic conditions in near-shore, shallow-water areas vary significantly in time and space. Climatologies and infrequent, large footprint remote sensing measurements cannot capture the small-scale, three-dimensional details that are of interest for many applications; timely in situ measurements are also needed. However, standard techniques for collecting the requisite in situ data are expensive and time consuming. Ship time, for example, is expensive. Oceanographic instruments are often expensive to purchase and maintain and require highly trained personnel to deploy and retrieve. Bottom depth and composition can change significantly over small distances and short time periods, posing hazards to ships and equipment. Environmental conditions can be extreme: tidal currents can reach several knots and change direction 180° in 12 or 24 h; temperature, salinity, and other parameters vary over wide ranges; wind and wave conditions can change rapidly and drastically; biological productivity is often high, resulting in biofouling. Nearness to shore and high biological productivity often lead to high densities of human activity and, thus, heightened potential for inadvertent or intentional vandalism.

Researchers at the Naval Research Laboratory (NRL) and the Woods Hole Oceanographic Institution (WHOI) combined their efforts to help solve some of these difficulties in a project given the acronym XMOOR: Expendable Oceanographic Mooring (Frye and Boyd 1996; Frye et al. 1997). The following system properties were established as goals for the project:

1) A reasonably inexpensive but durable moored platform
Rationale:

- Reduced financial impact if lost, stolen, or destroyed
- Cheap enough to allow use of multiple units for spatial coverage
- Easily recoverable and reusable, if desired

2) Small and compact
Rationale:

- Easy deployment by one or two untrained persons
- Multiple units can be carried on a small boat

3) Adaptable for use with a wide variety of small, low-power sensors
Rationale:

- To take advantage of emerging technologies, including MEMS (micro electromechanical systems)

4) Two-way telemetry
Rationale:

- Real-time data availability, if desired

- Remote command and control capability (e.g., change sampling rate, send selected data, etc.)

5) Internal data storage for post-recovery data download
Rationale:

- Alternative way to obtain data besides telemetry

6) Self-deploying
Rationale:

- Rapid deployment by untrained personnel

7) Depth-adaptive over 10–100 m (or more)
Rationale:

- No accurate knowledge of depth needed
- No field configuration needed

8) Suitable for rapid response deployments from a variety of platforms
Rationale:

- Needed for military and civilian purposes

9) Design to permit straightforward adaptation to air and underwater deployment schemes
Rationale:

- Particularly useful for military applications

We recognized at the outset that not all of these objectives could be fully attained with present technology. For example, while many extremely small, inexpensive, low-power sensors are theoretically achievable through MEMS technology (e.g., hydrostatic pressure sensors), most are not yet available (see, for example, Bryzek et al. 1994; Malafsky 1996). Similarly, present-day two-way data telemetry systems are not yet low-power, small, and available everywhere. However, most (if not all) of these limitations are likely be resolved within 5 to 10 yr. Progressively improving implementations of the XMOOR concept will be possible. Nevertheless, the prototype XMOOR has been shown to be a useful system even with present-day technology.

In the following sections we describe the current XMOOR system and its components in detail and present results of test deployments to date. We then briefly discuss what we see as the most promising near-term future improvements to the system.

2.0 GENERAL INSTRUMENT DESCRIPTION

A summary of XMOOR is presented in Table 1. Figure 1 is a predeployment photograph of the packaged unit and Fig. 2 is a cutaway view of the predeployment package. Figure 3 presents a schematic of the XMOOR after deployment.

At the top of the package in Fig. 2, a schematic of a self-inflating buoy enclosed in a breakaway housing can be seen. The buoy supports the mooring and provides a platform for meteorological sensors and data telemetry antennas. An instrument housing immediately below the buoy contains radios, data acquisition and telemetry electronics, sensors, and batteries. A view of an inflated XMOOR surface buoy and the instrument housing below it is given in Fig. 4. Below the instrument

Table 1 — XMOOR System Parameters

SIZE:	Length 1.67 m (65.6 in.) Diameter 17.5 cm (6 7/8 in.)
WEIGHT:	57 kg (125 lb)
OPERATIONAL RANGES:	Water depth: 10–100 m Current: 0–150 cm/s (0-3 kt) Duration: 0–3 mo
SENSOR CONFIGURATION:	Atmospheric: air temperature barometric pressure Oceanographic: temperature (up to 25 depths) conductivity (up to 3 depths) pressure (up to 2 depths)
TELEMETRY CAPABILITIES:	Long range: ARGOS (256 bits per transmission) Short range: VHF (9600 bits/s) Internal to mooring: Inductive (1200 bits/s)
DATA COLLECTION RATES:	Configurable prior to deployment or remotely by RF link
DEPLOYMENT:	Deployable by one or two untrained persons

housing is the line canister, a nylon cylinder containing up to 100 m of coiled mooring line and thermistor strings (Fig. 5), and one or more instrumentation and electronics packages or "pucks" (Fig. 6). Finally, below the line canister is an aluminum anchor canister containing 15 m of chain and a collapsible embedment anchor (Figs. 5 and 7). The standard sensor suite includes meteorological sensors at the surface (air temperature, barometric pressure) and oceanographic sensors from the sea surface downward. The oceanographic sensors are sea surface temperature, sea surface conductivity, subsurface temperature profile via one or more thermistor strings, midwater CTD (conductivity-temperature-depth) measurements via sensors in the pucks at selected locations and near-bottom CTD measurements from instrumentation in a puck mounted in the line canister. Table 2 summarizes the major system components.

An XMOOR is deployed by simply throwing it over the side or letting it slide into the water (Fig. 8). Contact with seawater causes the flotation buoy to inflate and the collapsed telemetry mast to extend (Fig. 9). Present telemetry includes a spread-spectrum, two-way digital radio at 901 MHz and an ARGOS PTT at 401 MHz. If telemetry frequencies are changed, the active length of the appropriate antenna enclosed in the telemetry mast can also be adjusted. Buoy inflation disconnects the line canister and anchor assembly from the surface canister and buoy module, allowing them to fall free. As they fall, they pull the mooring line, thermistor string, and any instrument/electronics packages (pucks) that may be attached out from the line canister. When the canister and anchor assembly hit bottom, the line lockup mechanism closes and the mooring line can no longer pay out. The anchor assembly also releases. Wind and currents pull out 15 m of quarter-inch (0.64 cm) chain and open and embed the collapsible anchor. Shifts in direction of the tension on the chain and anchor will release the anchor, which then re-embeds in the new direction. The final XMOOR configuration after full deployment is diagrammed in Fig. 3.

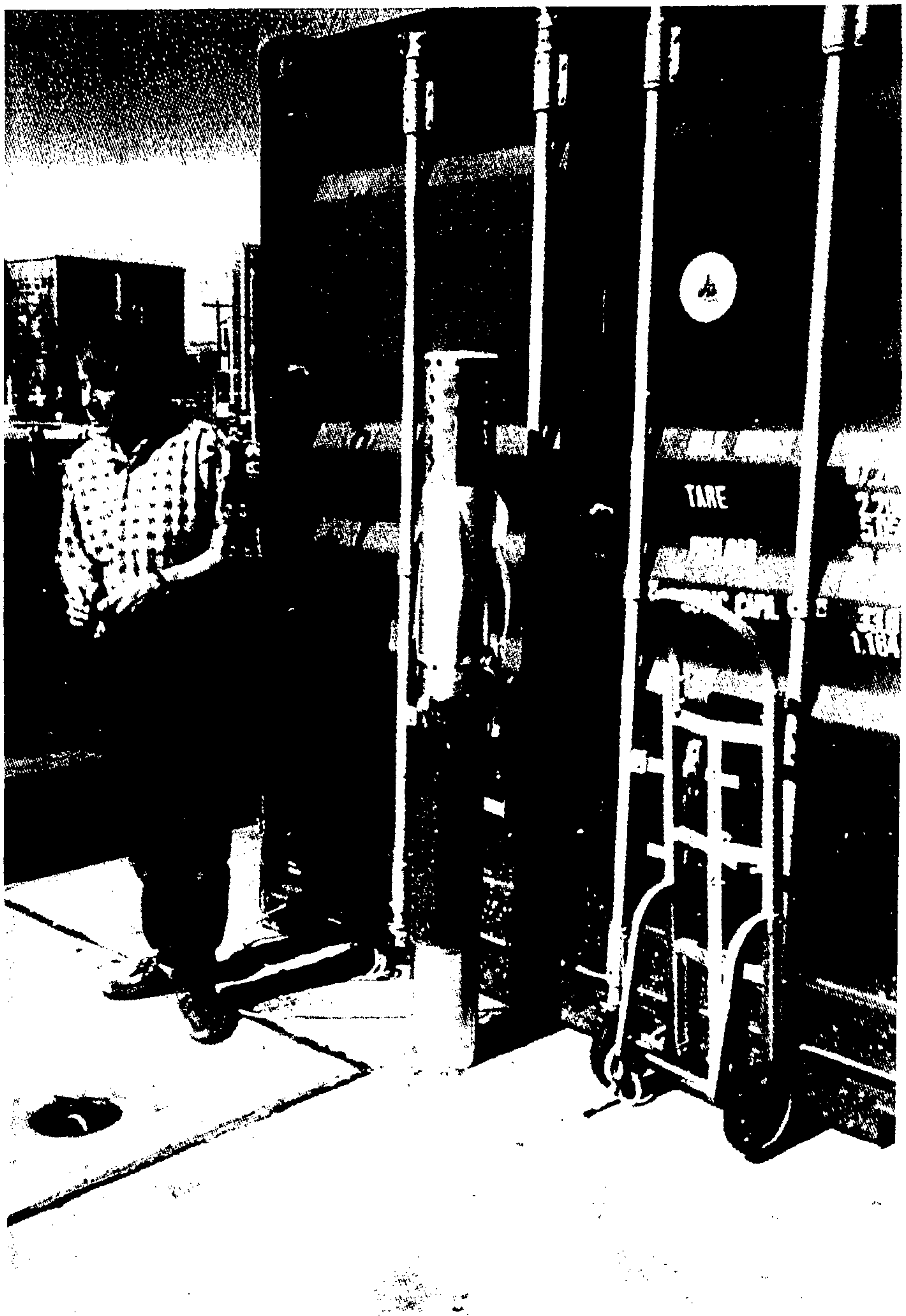

Fig. 1 — XMOOR packaged and ready for deployment

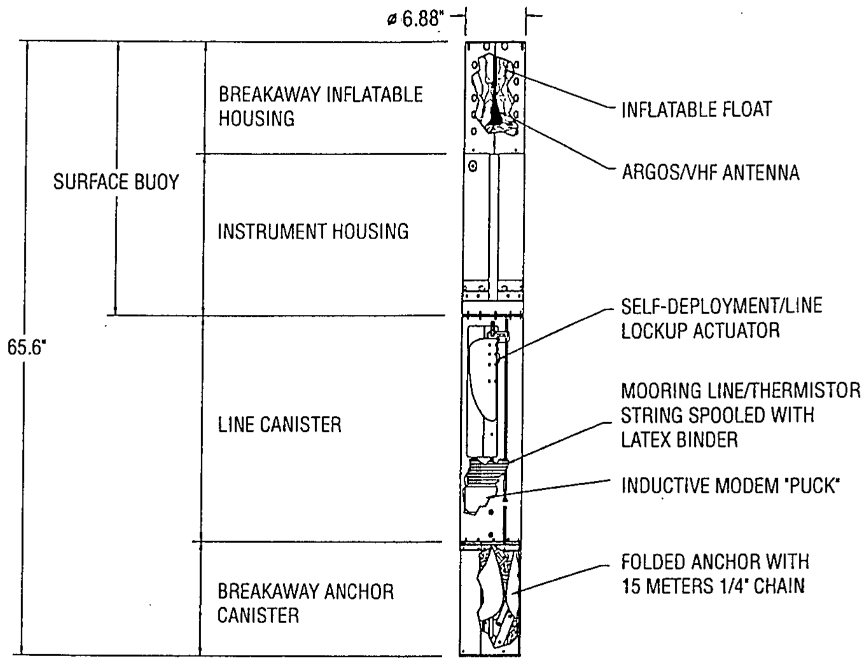

Fig. 2 — Cutaway view of XMOOR prior to deployment

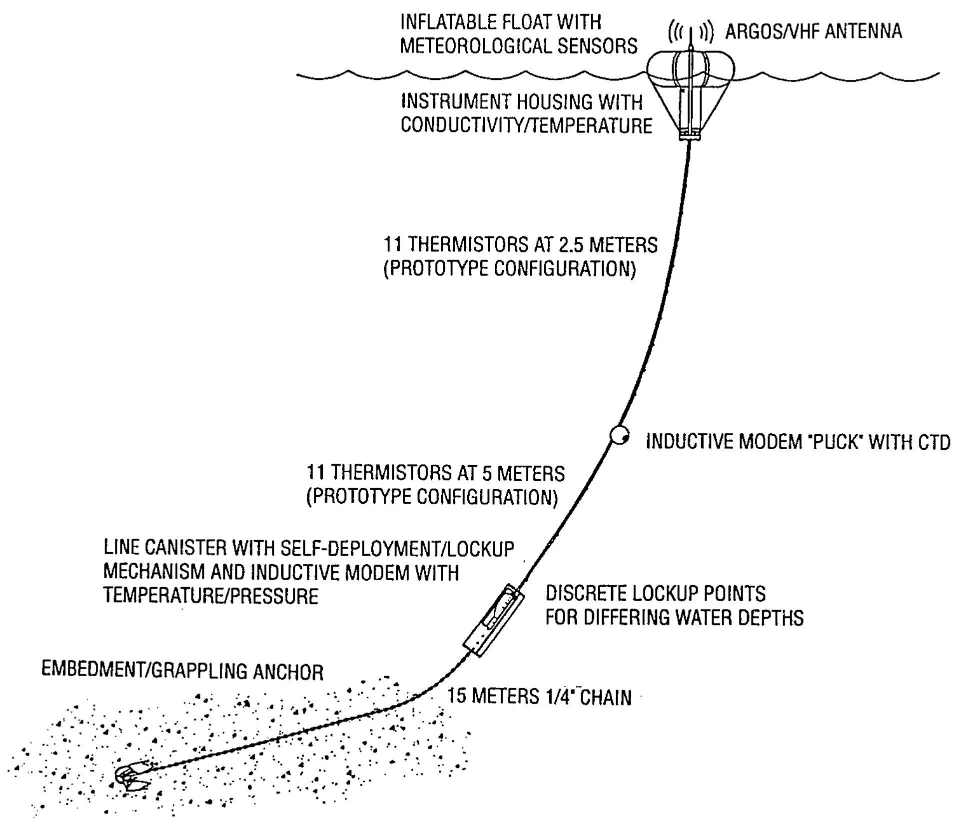

Fig. 3 — XMOOR after deployment

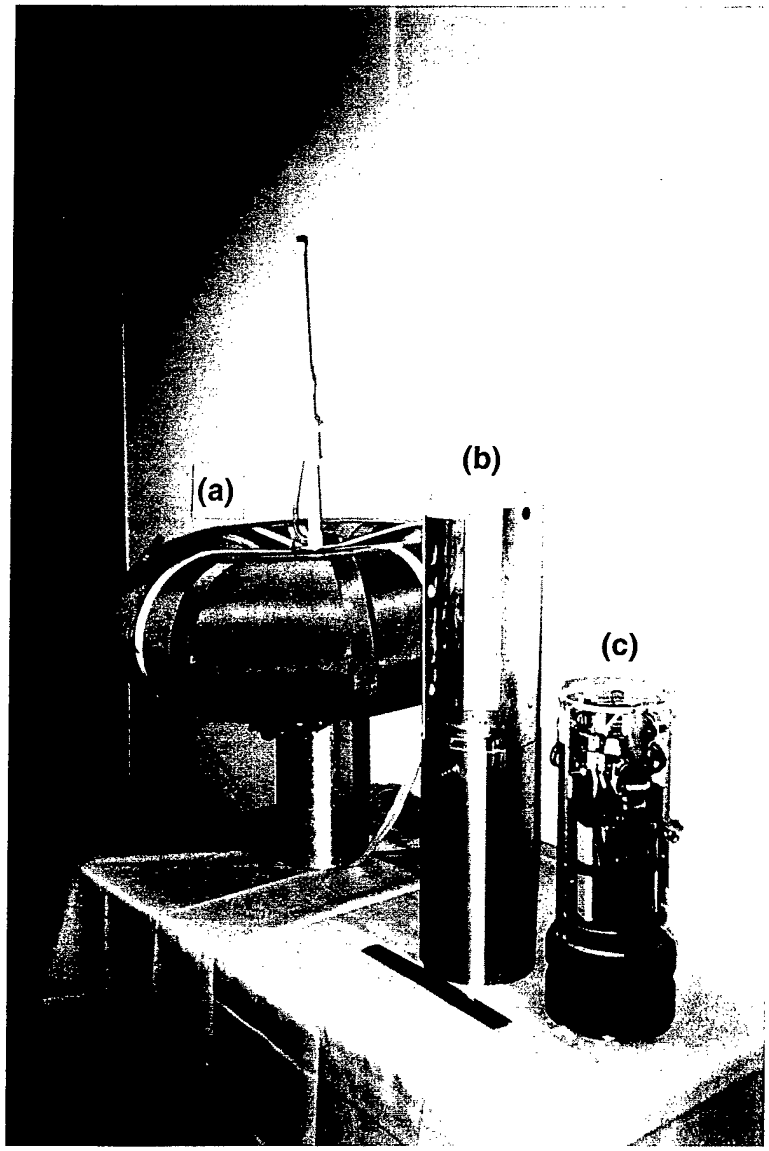

Fig. 4 — (a) Inflated XMOOR buoy, (b) surface instrument housing, and (c) instrument chassis. The extended RF telemetry antenna can be seen above the inflated buoy. Above the second instrument housing (b) is the enclosure into which the uninflated buoy and the collapsed antenna fit prior to deployment. The scale is 12 in. (30.4 cm).

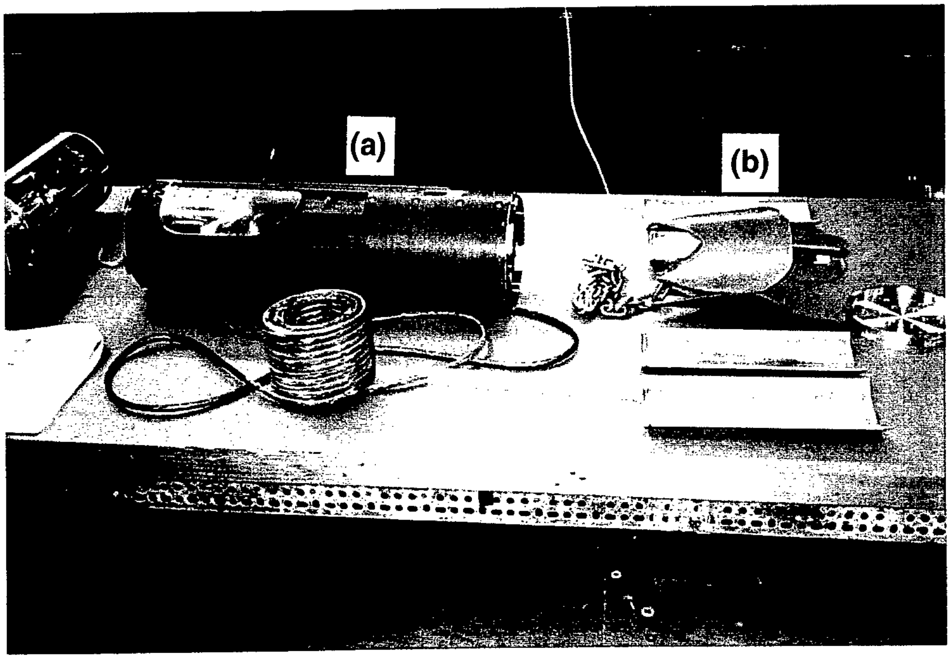

Fig. 5 — (a) XMOOR line canister and coiled mooring line/thermistor string combination and (b) collapsible anchor. The light-colored wing on the line canister is the wing flap. It is hinged onto the line canister on the left. The wing is held out in a horizontal position by water pressure as the line canister and anchor canister fall down through the water. When the wing flap is open, the mooring line and thermistor string can unspool from inside the line canister. When the unit hits bottom, the wing flap snaps shut and the lockup mechanism is actuated, which prevents any additional line from unspooling. The scale is 12 in. (30.4 cm).

The XMOOR surface float has 200 lb of reserve buoyancy and will become a drifting buoy rather than a moored instrument should the unit be deployed in water deeper than its maximum limit. When the maximum amount of line pays out, the anchor chain and anchor both release. The fully extended XMOOR then drifts with the current until such time as the anchor grabs bottom or comes into contact with some other object (empirically, some fisherman's fishing gear or crab trap).

3.0 SURFACE COMPONENTS

3.1 Flotation

The surface float (Figs. 4 and 9) is a 76 cm (30 in.) toroid of urethane-coated nylon material bolted to the top of the electronics housing. The manufacturer was the Patten Co. of Lakeworth, FL. The float also supports the antenna and meteorological sensors. Either CO_2 or N_2 is used for inflation. Most self-inflating systems use liquid CO_2 as the inflation gas, but CO_2 diffuses through most suitable float materials fast enough to make it unsuitable for deployments longer than a few weeks. Instead, N_2 must be used for the longer deployments. Using compressed gas cartridges (from Leland, Ltd., of South Plainfield, NJ), four cartridges of CO_2 or eight cartridges of N_2 are required to inflate the buoy. (Since CO_2 is less expensive than N_2, CO_2 is used for short deployments.) When inflated, the buoy has a reserve buoyancy of 200 lb and floats very high in the water. The cartridges are screwed into fittings on the bottom of the buoy and are pierced by individual actuators following seawater immersion and dissolution of small, water-soluble tablets. Inflation

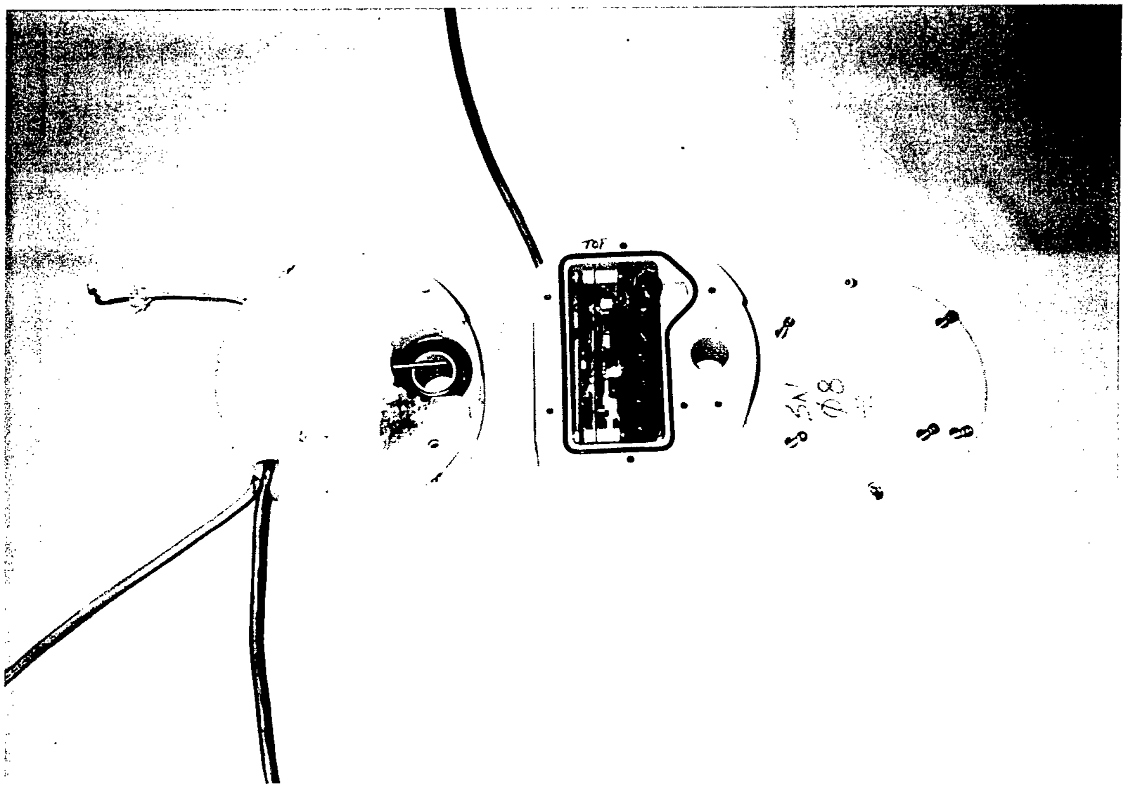

Fig. 6 — Two XMOOR mini CTD "pucks." The one on the left is closed; the one on the right is turned over and opened to show the cavity in which the electronics and batteries reside. A puck contains a mini CTD (see text), batteries, inductive modem, and electronics for both the mini CTD and the thermistor string connected to it. The puck diameter is 15.25 cm (6 in.) in diameter.

occurs very rapidly. The unit goes no deeper than several meters before the expanding float pulls it to the surface.

3.2 Surface Sensors

The sensors mounted on the surface unit measure atmospheric pressure and temperature at a height of about 30 cm. The bottom of the electronics housing is normally fitted with one or two temperature sensors and an inductive conductivity cell.

The atmospheric pressure sensor unit is a Motorola MPX4115AS, a temperature-compensated semiconductor strain gauge with a voltage output linearly dependent on atmospheric pressure. Relative to metal foil strain gauges, the semiconductor strain gauge gives up some long-term accuracy for higher signal output and lower cost. However, the sensor works very well for relative day-to-day variability. Resolution over all atmospheric pressure ranges is less than one millibar. Accuracy is ±10 mb without calibration.

The air temperature sensor is a Teflon® coated epoxy bead thermistor from Yellow Springs Instruments with a nominal resistance of 10±1% kohms @ 25°C. This 1% tolerance thermistor is more expensive than greater tolerance thermistors, but does not require calibration for accuracies of ±0.5°C. If calibration is performed, accuracy is about 0.1°C. Temperature resolution over the range of –10 to +40°C is less than 2 mdeg.

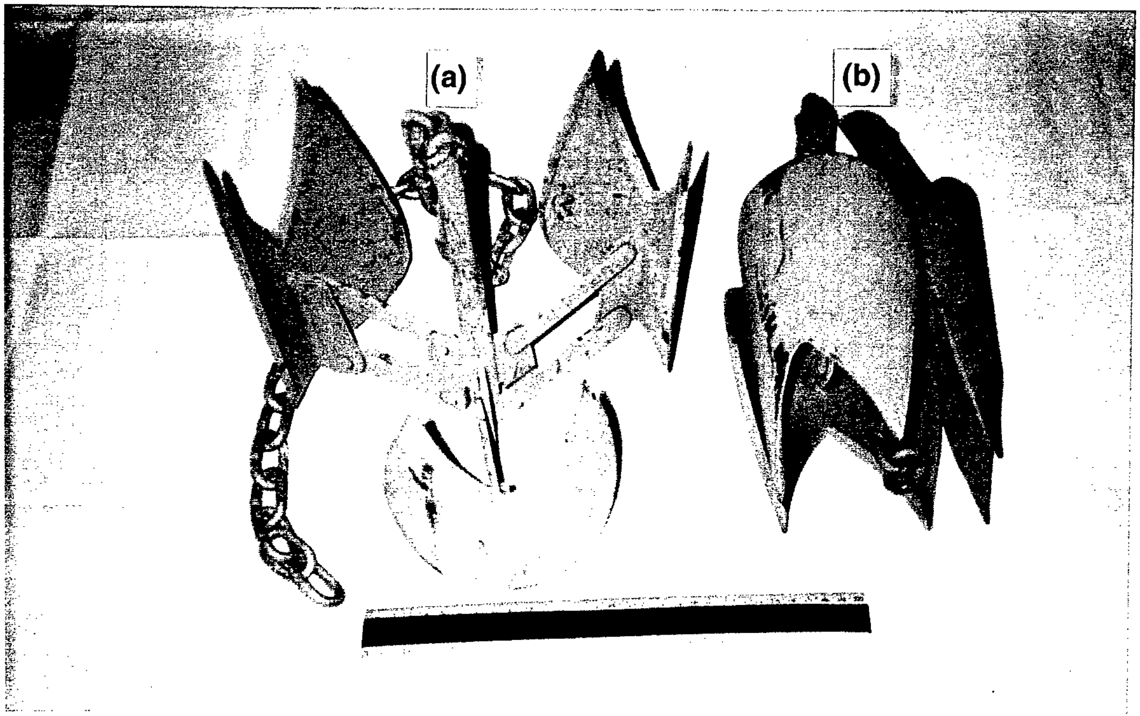

Fig. 7 — View of XMOOR collapsible anchor: (a) open and (b) closed. The scale is 12 in. (30.4 cm).

Table 2 — Major XMOOR Components

Surface	Flotation
	Surface sensors
	Meteorological:
	   Air temperature, barometric pressure
	Oceanographic:
	   Sea surface temperature
	   Surface conductivity (optional)
	VHF/ARGOS antenna
	Instrument housing with surface electronics

Midwater	Mooring line Thermistor string(s) Inductive return wire (in some versions) Instrumentation puck (optional)
Bottom	Line canister with remaining line and optional instrumentation puck Anchor chain Collapsible anchor

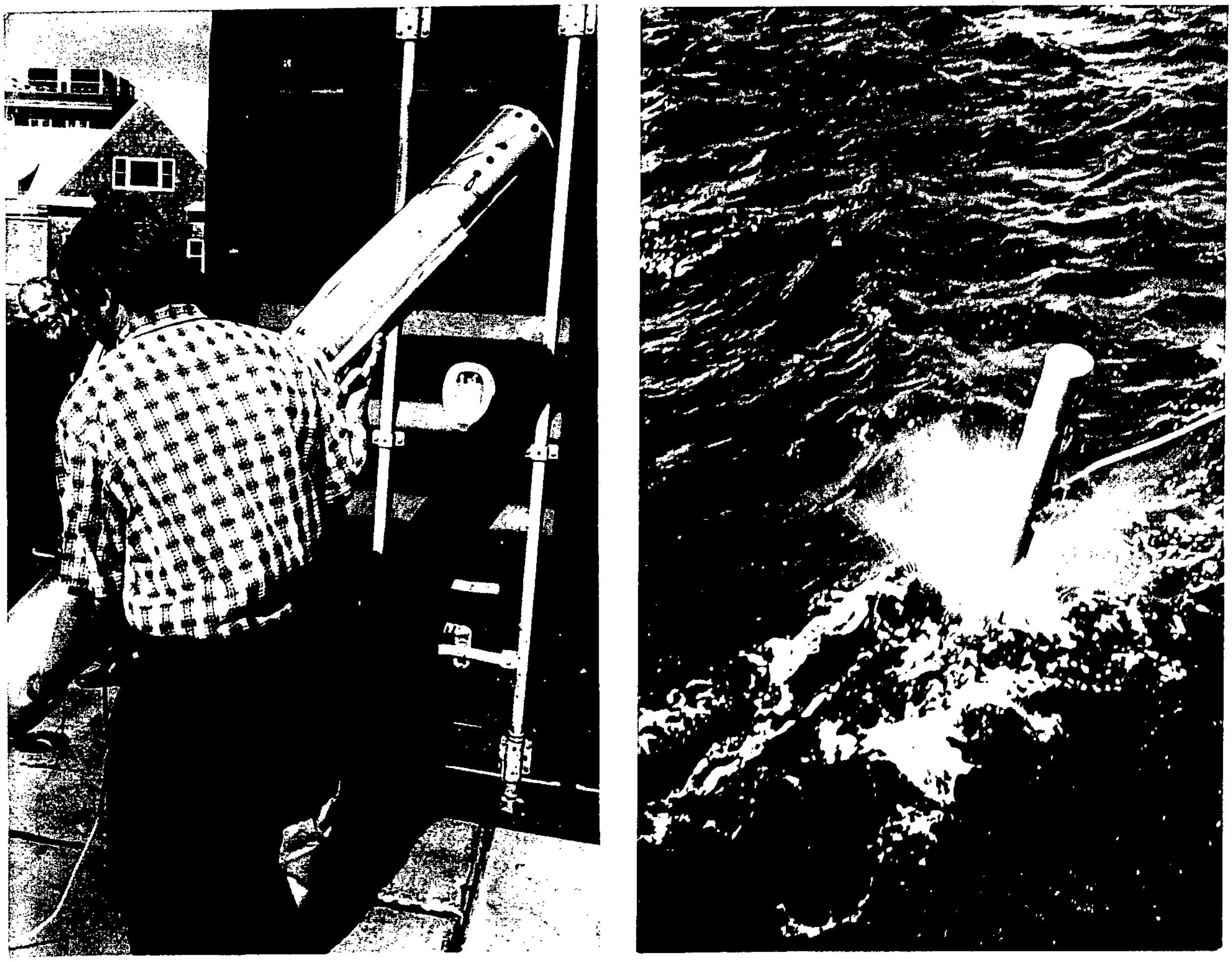

Fig. 8 — Two people can easily deploy an XMOOR by picking it up and throwing it over the side into the water

The two meteorological sensors are potted in a nearly clear polyurethane with a 25 cm length of quarter-inch (0.64 cm) tygon tubing extending out as a pressure port. The thermistor is mounted and potted so that the thermal mass effect of the polyurethane is minimized. The bare thermistor has a time constant of 25 s in air, which increases to about 2 min when encapsulated. The meteorological unit is mounted under the disk of the antenna mount on the top of the flotation toroid to minimize the effects of solar radiation and wave splash. Tests were run on the tubing pressure port to verify that water would not penetrate up the tubing to the pressure sensor during and after deployment.

The sea surface temperature (SST) sensor on the bottom of the surface pressure housing is the same as for air temperature: a Yellow Springs Instruments Teflon® coated epoxy bead thermistor with a nominal resistance of 10±1% kohms @ 25°C. The time constant for the bare sensor is 2.5 s in water. When enclosed in its protective aluminum mounting sting, the time constant increases to 30 s. Accuracy without calibration is ±0.5°C; with calibration, at least ±0.1°C. Resolution over the range of −10 to +40°C is better than two mdeg.

The conductivity sensor has been a short-stem inductive sensor from Falmouth Scientific, Inc. (FSI). This sensor has the advantage of durability and resistance to effects of biofouling, but the

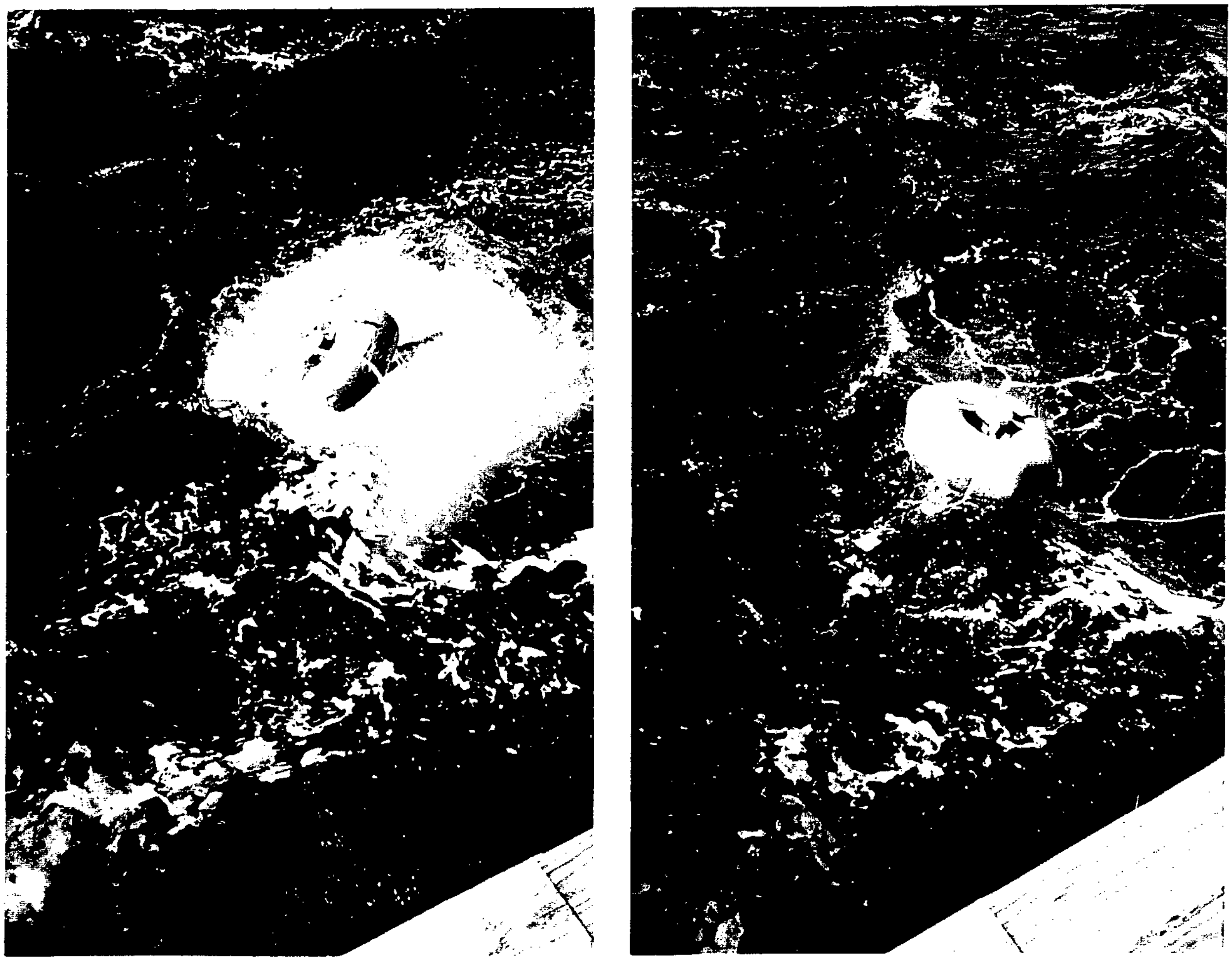

Fig. 9 — Within a few fractions of a second after an XMOOR enters the water, the buoy inflates and pops to the surface, releasing the collapsed RF antenna. Note the antenna is still collapsed in the view on the left and is beginning to extend in the view on the right.

disadvantage of being relatively expensive (order of $850) and large, particularly with the associated electronics. It is mounted in the base of the surface electronics canister. A thermistor comes with the unit, mounted in the toroid section near the stem of the conductivity sensor, but the thermistor's time constant is so long due to the surrounding thermal mass that it cannot be used with the conductivity values to compute salinity under most oceanographic conditions. Instead, the SST signal is used after the fact to compute salinity. The FSI conductivity sensor has a quoted resolution of 0.005 mmho/cm and accuracy of ±0.025 mmho/cm.

3.3 Instrument Housing and Surface Electronics

Electronics components to perform many of the necessary XMOOR functions are mounted in an aluminum chassis that slips into the surface instrument housing (Fig. 4). These components provide various functions, including external and internal communications and control, data aggregation and storage, and power supply, which we describe in the following sections. The instrument housing itself is aluminum with an alodyne finish and a base of black Delrin.

3.4 External Command, Control, and Data Telemetry

The remote communications systems consist of a VHF spread-spectrum radio command and control link and a system state-of-health link via the ARGOS satellite data collection system. Other options, such as cellular phone links, could also be implemented if more appropriate for a given application. Both the spread spectrum radio link and the ARGOS link have serious shortcomings, but we selected them as the best compromises among the available options. The state-of-the-art in long-distance data communications is evolving rapidly, and better systems will become available in the not-too-distant future.

A two-way radio link between the XMOOR and the remote user was considered essential for most applications. Both transmission of data from the XMOOR to the user and transmission of commands from the user to the XMOOR are possible. Initially, a standard UHF link was implemented, but frequency allocation problems proved effectively insurmountable. A spread spectrum link (we use a GINA Model 5000 or Model 6000 for both transmission and reception) solved this problem. The GINA radio operates in the 902-928 MHz band allocated by the FCC for spread spectrum use, and an FCC license is not required. In the XMOOR itself, the system may be set to transmit data on every data acquisition cycle or only when requested, when data from all or part of memory is transmitted. The user may send commands to the XMOOR requesting data transmission, transmission of certain status or state-of-health variables, immediate initiation of a data acquisition cycle, or modification of control variables such as sampling frequency. The present radio link functionality is summarized in Table 3; this would be expanded with experience.

A serious limitation of any line-of-sight radio link is its limited range of only a few miles. This is a particular problem with a low-profile system such as XMOOR. To ensure that it would always be possible to monitor an XMOOR's status and position, we have also installed an ARGOS satellite communications link (Seimac SmartCat PTT). This link is relatively expensive, data throughput is very limited, and the link does not allow two-way communications. However, in cases where there

Table 3 — XMOOR Radio Link Commands

DUMP	Send program control variables now Up to 128 variables specified in program
MODIFY	Modify program control variable User specifies variable by number
STATUS	Send status variables now[1]
PING	Initiate data acquisition cycle now
OFFLOAD a b	Offload data now, from address a to address b
END	Terminate communication link

[1] Status variables are:

Time now
Time of next data acquisition cycle
Time of next ARGOS window
Battery voltage
Leak detection
Pointer to flash memory position
% flash memory used

is no nearby shipboard or land monitoring station, the link can be very worthwhile for detecting problems or acquiring summaries of data. In particular, if the unit drifts or is picked up, its position can be monitored and attempts made to retrieve it.

One reason for limited ARGOS data throughput is that satellite passes only occur about 4 to 6 times per day, depending upon latitude (more opportunities occur closer to the poles). During each window, the satellite is in view long enough for one to five messages to be sent, but not every message is successfully received. In addition, each ARGOS message is only 256 bits long, and each XMOOR data acquisition cycle typically creates considerably more data. Our solution is to send only a subset of data values. During each window, two messages are sent repetitively: the first message contains state-of-health variables and the second message contains selected data variables. Usually within about 36 h, data values from all sensors are sent and performance of all sensors can be evaluated.

Common practice is to configure an ARGOS PTT to transmit every 90 s whether satellites are present to receive the message or not. To save battery power, XMOOR instead transmits only if a satellite is in view. We compute an almanac for the general location and time period of interest and load it into the system controller memory (Sec. 3.6) as part of pre-experiment preparation. After deployment, this almanac tells the controller when the next satellite will be available and, hence, when to turn on the PTT. An option for continuous transmission (every 90 s) is also available.

At times, data transmission may be undesirable, unreliable, or impossible, and the user may wish to download the data after the unit is retrieved. To handle this contingency, all data are immediately stored after collection in non-volatile flash memory (Sec. 3.6).

A compressible sleeve antenna is used for both RF telemetry systems (see, for example, Fig. 4). It is mounted on a two-part extending PVC rod at the top of the flotation toroid. The radiating lengths are cut at quarter-wave lengths for 901 MHz and 401 MHz for the spread spectrum radio and ARGOS PTT, respectively. The mast is compressed during shipping and is released when the surface float is inflated, being extended to its full length by an extension spring. The antenna has worked satisfactorily in our tests, but has in principle several shortcomings. The radiating wires are located alongside each other in the upper part of the mast, which means each active element shadows the other to some extent. The design also radiates predominately horizontally outward rather than up (which may be a disadvantage to airborne and satellite receivers, but actually is of benefit to shipboard users). Future work to evaluate in more detail the performance of this and a few other possible designs would be desirable.

3.5 Internal Communications and Data Acquisition

With most of the current XMOOR units, inductive telemetry (Frye et al. 1993; Frye et al. 1996) at 1200 baud has been used for internal communication of data from subsurface sensors to the surface command and control unit. Inductive telemetry is based upon the transformer concept, where the primary is a split ferrite core with multiple turns clamped around the mooring wire, and the secondary is the mooring line, a 3/16 in. (0.48 cm) Vectran line with a single central conductor, creating a single turn. The secondary circuit is completed with a seawater return path. However, frequent mysterious, hard to isolate problems associated with the seawater return have led us to substitute (in some units) a Teflon® coated copper return wire for the return path. The data are transmitted by applying voltages to the ferrite core, which then inductively transfers the signal onto the mooring line. The signal is received and reinterpreted as data by the master inductive modem and the system controller in the surface canister (Sec. 3.6).

An instrumentation/electronics package, or node, consists of a ferrite core, an inductive modem, sensors, ancillary electronics, and a power source. In principal, the package may be clamped on to the mooring wire at any location without leakage-prone electromechanical penetrations of the wire. Either two or three nodes have been used in the XMOORs constructed up to now: a surface node, sometimes a midwater node, and a bottom node (Fig. 3). The midwater and bottom node electronics are housed in the instrumentation/electronics pucks described in Sec. 4.3 and pictured in Fig. 6.

An inductive modem and a node controller are located in every node. When the inductive modem receives a wakeup pulse from the system controller (Sec. 3.6), it signals the node controller to execute a data acquisition cycle. The data sampling rate is determined by how often a wakeup pulse is sent. The maximum data sampling rate is limited by how often the system controller executes the data acquisition portion of the program and sends a wakeup pulse. Currently this is every 32 s, so the absolute maximum sampling rate is somewhat more than every 32 s. Sampling rate issues are discussed further in Sec. 3.6.

The node controller CPU is a Motorola 6811 chip with 12 Kbytes of PROM memory. The present design allows up to 15 analog data channels (including thermistors or sensors that can be configured to simulate a resistive load) and up to four auxiliary voltage channels for such sensors as conductivity and pressure. A/D conversion accuracy is 15 bits, with 16-bit resolution (19-bit resolution is possible with firmware modification). When signaled by the inductive modem, the node controller initiates a data acquisition cycle, sampling all channels once and sending the values to the modem for further transmission to the master modem in the surface instrument housing.

3.6 System Control

Overall system control is handled by a microcomputer and circuitry on the system control interface board (SCIB) mounted in the surface electronics canister. The microcomputer is an Onset Tattletale Model 5 with an additional 2 MB of flash memory for non-volatile data storage.

The system control software in the Tattletale has three sections: data acquisition, command and control, and ARGOS telemetry. The SCIB wakes the Tattletale up every 32 s. The main part of the Tattletale program reads the real-time clock and then calls each program section in turn. Each program section determines if it should execute before the next 32 s wakeup time. If not, the current section returns to the data acquisition (main) section. If so, the section does not return, but waits until the appropriate time is reached and then executes its function.

When a data sampling time is due, the data acquisition section sends a wakeup pulse to the master modem located in the surface housing and waits to receive data back from the master modem. The master modem generates another wakeup pulse that is sent down the mooring line to the individual nodes. After the modem in each node detects the wakeup pulse and powers up, it powers up its associated node controller. The node controller executes a data acquisition cycle and sends the data back to its inductive modem. That modem then places the data on the moring line, from which the signal is acquired by the master modem. To prevent collision of data transmissions, each node has an allotted time slice for sending data. After the data are transmitted, the node controller and its modem and associated circuitry powers down. The master modem sends the data signal on to the Tattletale. After receiving as many data transmits back as there are data nodes or after a preset time period (maximum of 16 s), the program proceeds to the next step. Should the data transmit switch be set, the Tattletale immediately sends data to the spread spectrum radio link.

Data are then stored internally to non-volatile flash memory and the program returns to the main section.

Following data acquisition, the command and control (radio link) section is executed. The program checks time to see if a radio transmission is due. The transmit time is preset by the user and if more than one XMOOR is in use, transmit times are staggered to prevent interference. If a transmission is due, the radio is powered up and the program checks for the "beacon" switch on. If the beacon switch is not on, the program returns to the main program. If the beacon switch is on, the program initiates a transmission indicating the XMOOR is listening for commands from the user and is in a state that is able to execute them. The user may then issue the commands listed in Table 3 and have the appropriate responses sent back. If another data acquisition/data transmission cycle occurs while the user is connected to the XMOOR, the connection is temporarily broken while the XMOOR transmits the data. Connection with the user is broken either by the user issuing an "END" command or by no communications from the user for 60 s. The radio is then powered down and control returned to the main section.

Finally, the ARGOS link section is executed. First the almanac is checked to see if a transmit window is open (that is, if a suitable satellite is available to receive ARGOS transmissions). If not, the program checks to see if the ARGOS PTT is still on from a previous cycle. The PTT is shut down, if appropriate, the program returns to the main section, and the Tattletale is shut down to low-power mode. If the window is open, however, the ARGOS PTT is turned on and the two ARGOS messages are constructed and sent to the PTT, which sends the messages consecutively every 90 s. PTT power is left on until the next time the ARGOS link section of code is executed.

The XMOOR sampling rate is determined by a user-set parameter that tells the Tattletale how frequently to issue a wakeup pulse. There are certain inherent limitations on how fast that sampling rate may be. First, the SCIB awakens the Tattletale only every 32 s. Within that time, the Tattletale executes programs that take data, checks for a radio communications request, and checks for servicing the ARGOS PTT. The thermistor string time constants are 35 s (Sec. 4.2). This automatically limits the sampling rate to perhaps once every 40 s, or roughly once per minute. However, with such a sampling rate, radio communications are effectively impossible since the Tattletale will be constantly breaking communications to execute a data acquisition cycle. Hence, we feel a sampling rate of much faster than once every 5 min or so is impractical, at least if radio communications are permitted. XMOOR was designed for applications requiring sampling rates on the order of every 10 or 15 min or greater. Any adaptation of XMOOR to higher speed sampling would probably involve changes in hardware, software, and software approach.

3.7 Miscellaneous Components

Power for the surface unit components is supplied by 21 alkaline D cells: three parallel banks of seven each, providing a usable DC voltage range of 10.5 V down to about 7 V. Greatest power consumers are the spread spectrum radio and the ARGOS PTT; the XMOOR power lifetime will usually be controlled by how often these are used.

An electronics board termed the SCAUX (system controller auxiliary) board is mounted above the SCIB board. It contains an RS-232 level converter chip, a power regulator circuit, and the inductive modem wakeup circuit. The converter chip is necessary for the Tattletale to communicate with the spread spectrum radio. The power regulator circuit supplies suitable power to the spread spectrum radio, which requires 12 VDC rather than the 10.5–7 VDC available from the battery pack. Finally, when signaled to do so by the SCIB, the inductive modem wakeup circuit produces

a signal on the mooring line that is passively detected by the remote inductive modems, which then turn themselves on. This passive wakeup circuitry in the inductive modems allows very small battery packs to be used to power the in situ oceanographic sensors. Four alkaline AA batteries are capable of powering the sensors for up to 3 months, depending on the data acquisition rate.

An umbilical interface connection is also supplied to allow communications between the Tattletale system controller and an external computer. A port through the outside wall of the instrument housing can be unscrewed and a connector inserted to allow an external computer to download a new control program into the Tattletale or to download stored data.

A leak detect circuit has been placed on the SCIB. A leak detect sensor is a simple circuit with two wires leading down to a low point in the surface instrument housing. If water collects there, a connection is made between the two wires and the Tattletale can detect a leak detect signal. The information can then be relayed to the user via the spread spectrum radio or ARGOS.

4.0 MIDWATER COMPONENTS

4.1 Mooring Line and Optional Inductive Return Wire

A 3/16 in. (0.48 cm) diameter Vectran line with a single, highly helixed central conductor was developed for the mooring line. It has a 1200 lb (5340 Nt) rated breaking strength, is very low stretch, and is not easily damaged by bending or abrasion. It packages easily into spools and deploys without kinks or snags.

In earlier XMOOR versions, a seawater return was used to complete the inductive circuit, but problems were frequently encountered that could not be unambiguously diagnosed and reliably eliminated. These were solved in later versions by substituting a 22-gauge, Teflon® coated copper ground return wire for the seawater return. This copper return path removes the variability of the seawater return path that was suspected to be a source of some of our problems, and it provides a constant data signal level and improved data reliability. In both configurations, polyester sleeving is used to attach the thermistor string to the mooring line. The mooring line, inductive return wire if present, and thermistor string are slipped into 0.25 in. (0.64 cm) braided polyester sleeving that holds the two or three wire bundles together in a "chinese finger" configuration. Use of the sleeving prevents any tensile loads from being placed on the copper wires.

4.2 Sensor String

The major complement of sensors is generally a set of thermistors on a multiconductor wire that connects to a node controller board located in a subsurface puck (Sec. 4.3) or in the surface housing. Any sensor that behaves like a thermistor could be placed on the string; that is, any sensor or sensor package in which the voltage applied to that sensor changes by an amount proportional to the value of the parameter being measured. At present, only temperature-measuring thermistors are available with those characteristics. Extremely useful MEMS sensors would be the ones measuring other parameters that are able to convert their values into something that appears as a variable resistance. Hydrostatic pressure and sound speed would be good first candidates for the other parameters.

A frequent sensor configuration has three nodes: a surface node and two subsurface nodes with two pucks, one midwater puck, and a second puck at the bottom in the line canister. The lower two

nodes each consist of a thermistor string and an instrumentation and electronics puck containing pressure, temperature and conductivity sensors, batteries, and the electronics needed for data collection and transmission. The upper thermistor string begins as close to the surface as desired and terminates at the midwater puck. The lower thermistor string begins below the midwater puck and terminates at the line canister puck. Another frequent configuration for quite shallow water is to use only one thermistor string that terminates at one puck in the line canister. The choice of having the string attach to a puck deeper in the water column rather than shallower is arbitrary; the reverse works perfectly well. However, wave and current action tends to be greater at shallower depths, and our standard approach of terminating downward tends to be the choice, placing less mechanical stress on the connection. Thermistors for present XMOORs have been placed 5 and 2.5 m apart. Closer placement poses no problem except that the present node controller design allows a maximum of 15 analog channels.

The thermistor strings have been made of eleven 28-gauge conductors surrounding a Kevlar strength member and a single, larger gauge central return conductor. Each thermistor is connected in-line to one of the 11 outer wires, which are then connected at the far end to the central conductor wire. The return wire is the reference voltage source that powers each of the thermistors when selected by the multiplexing electronics in the node controllers located in the pucks. The manufacturer of the thermistor strings has been Daycon Systems, Inc., of Fountain Valley, CA, using technology developed for constructing very small strings for use on Navy drifting buoys (Selsor 1993).

The thermistor beads used are Thermometrics R60 glass-coated NTC (negative temperature coefficient) beads with a time constant of about 300 ms in water. Polyurethane potting is applied to the thermistor after each is installed in the string and increases the time constant to about 35 s. The nominal resistance is 10±25% kohms @ 25°C. The loose tolerance of 25% (compared with the 1% tolerance, for example, for the air and SST thermistors) reduces the cost dramatically, but makes calibration necessary. Accuracy after 5-point calibration with a quartic polynomial is about ±0.15°C; resolution over the range of –10 to +40°C is less than 5 mdeg.

4.3 Instrumentation Puck

The maximum number of thermistors or thermistor-like sensors that can be connected to the present design of node controller is 15. An XMOOR with one thermistor string of 15 or fewer thermistors may be connected directly to the surface node controller, and we have done this in some deployments in very shallow water. However, in many cases, more thermistors are desired. In addition, sensors for parameters such as hydrostatic pressure (from which depth is derived) and conductivity are often desired at subsurface locations. Our solution was to design—with the assistance of FSI—a relatively small, self-contained instrumentation puck that is clamped onto the mooring line at various subsurface locations (Fig. 6). Within the puck is a node controller, an inductive modem, a 3-mo battery pack, and a ferrite toroid that encircles the mooring cable and transmits the signal inductively to the mooring line. A thermistor string connects to the puck's node controller, as well as a pressure sensor, a platinum resistance thermometer, and—in some versions—a conductivity sensor. The data from all these sensors are sent up the mooring line to the master inductive modem in the surface unit.

The conductivity sensor in the puck is a specially designed version of the FSI mini CTD used at the bottom of the surface canister, having an accuracy of ±0.025 mmho/cm and a resolution of 0.005 mmho/cm. The temperature sensor is a class "A" DIN platinum resistance thermometer manufactured by Sensor Devices, Inc., of Lancaster, PA. The pressure sensor is an absolute pressure

metal foil strain gauge with a full-scale range greater than the expected limits (for a maximum of 100 m, that means a 150 psi or better strain gauge). For air pressure we used a semiconductor strain gauge, but for the subsurface pressure sensors, we elected to use a metal foil strain gauge. Semiconductor strain gauges are less stable with time, have greater signal levels, and are a great deal less expensive, but we felt it was important to be able to more accurately determine the absolute depth of the sensors and the shape of the mooring catenary. The pressure gauges were manufactured by Sensotech of Columbus, OH, and have an accuracy of ±0.1% full scale. For a 200 psi rated gauge, this would be about 14 cm in depth.

An instrumentation puck is 15.25 cm (6 in.) in diameter and 7.66 cm (3 in.) high and is machined out of a single piece of glass-filled white Delrin with an O-ring sealed internal cavity that contains the electronics and batteries. In water, a puck weighs about 0.5 kg. The sleeving holding the mooring line and sensor string together is broken at each puck. The puck clamps around the mooring line, while about 8–10 cm of slack is left in the sensor string before it is connected into the puck. As a result, no mooring forces are felt by the sensor string.

5.0 BOTTOM COMPONENTS

5.1 Line Canister

Figs. 2 and 3 show pre- and post-deployment positions of the line canister, a nylon cylinder 61 cm long and 17.5 cm in diameter (Fig. 5). It typically contains up to 100 m of coiled mooring line and thermistor strings, up to two data collection pucks, and up to seven discrete lockup points for varying the amount of line deployed. The line canister is attached to the surface canister with a spring steel retainer that is released as soon as the surface buoy begins to inflate. The line canister and anchor canister as a unit fall downward, with the coiled mooring line and thermistor strings unspooling and paying out as the unit falls. If a midwater puck is included in the canister, it is pulled out as well. The line lockup actuator wing or drag wing is lifted upward by the action of the water flowing past and keeps the lockup mechanism from closing. When the canisters hit bottom, the wing folds down and the lockup mechanism closes. Under the action of current and wind, the remaining line and thermistor string will continue to pay out until the next attached lockup slide attempts to slip out of the canister. At that point, the slide is caught between a non-return spring and a tab on the actuator wing. When this locks, no more line payout can occur and the actuator wing locks so that it cannot reactivate. Any remaining line and instrument pucks are retained inside the canister by the lockup slide. Up to eight lockup slides can be used, but typically three have been attached to a 100 m long XMOOR at 30, 60, and 80 m with full line out at 100 m. The maximum and minimum scope of line can be controlled by the number and location of these lockup points.

5.2 Anchor Canister and Anchor

Beneath the line canister is the anchor canister, an aluminum cylinder with thin fall-away panels that release when the anchor hits bottom and the drag wing closes. The anchor canister contains 15 m of 1/4 in. (0.64 cm) chain and a folding embedment anchor (Figs. 5 and 7). Tension caused by the drifting surface float pulls the 15 m of chain away from the anchor. Further tension opens the collapsible anchor and the flukes catch and fully moor the whole system. The anchoring effect is through a combination of the embedment anchor, the anchor's deadweight, and the 15 m

scope of chain. The chain also provides compliance for wave motions and minimizes the angle of attack at the anchor stock. The upper end of the chain is attached to a metal fitting inside the line canister, providing a continuous mechanical connection between the anchor and the surface canister.

The size and weight constraints on XMOOR meant that deadweight anchors such as are often used in coastal moorings were not appropriate. Typical embedment anchors such as the Danforth need to be set and are vulnerable to dragging if the direction of the current changes. The Bruce anchor is a resetting embedment anchor, but Bruce anchors that would fit inside a 17.5 cm diameter cylinder do not have the necessary holding power. A new collapsible, three-fluke anchor was designed that re-embeds itself when current direction changes and has the holding power of a much larger Bruce-type anchor. The anchor embeds as it is dragged by the wind and current, re-embedding as needed in response to wind and current changes. As described in Sec. 6.0, the anchor also has the advantage of releasing when pulled more or less vertically, thus allowing easy recovery of the complete deployed XMOOR system.

6.0 DEPLOYMENT AND RECOVERY

An XMOOR deployment may be summarized as follows: a user simply throws or lets slide an XMOOR over the side into the water (e.g., Fig. 8). A useful procedure has been to ship the unit in a sufficiently long section (about 6 ft or 1.83 m) of 8 in. (20 cm) PVC pipe with one end permanently capped and the other end with a removable cap. For deployment, one cap is removed and the tube tipped over the side of the boat, allowing the XMOOR to slide out (Fig. 10). Seawater rapidly dissolves a set of water-soluble tablets, actuating CO_2 or N_2 gas bottles. The gas inflates the surface buoy to an initial pressure of about 2 psi. The buoy has 200 lb of reserve buoyancy when fully inflated and rapidly returns to the surface while inflation is still in progress. The inflating buoy pushes away the enclosing metal side walls and plastic top plate and pulls loose a pin retaining the collapsed telemetry antenna mast. The mast then springs up to an extended height of 0.5 m. The line and anchor canisters fall to the bottom, with the coils of mooring line and thermistor string paying out as they fall, as well as any instrumentation pucks. Upon hitting bottom, the mooring line lockup mechanism actuates, limiting the scope of line that pulls out of the line canister. The anchor canister falls open and the anchor embeds itself.

After deployment and successful data collection, the unit may be abandoned or it may be retrieved. Under most peace-time conditions, it would probably be desirable to recover an XMOOR, and we designed the unit to be durable enough for this. We have found retrieval to be quite easy, even from a small boat. The recovering vessel approaches close enough that the surface part of the XMOOR can be hooked with a boat hook. Then the surface unit is manually pulled on board and several people simply pull up on the mooring line/thermistor string combination. Unless the embedment anchor is caught on something, an upward pull unsets the anchor flukes and the anchor, and the rest of the subsurface gear is easily pulled to the surface. The thermistor string experiences no particular tension; tension is only felt by the mooring line, which has a 1200 lb rated breaking strength, far more than the weight of an XMOOR on land, let alone in water. We have recovered and deployed the same XMOORs several times with no particular problems except some damage to the very delicate glass bead thermistors in the thermistor strings. In the future, we plan to replace them with larger (but more durable) epoxy-coated thermistors. Problems will occur, of course, if the anchor is firmly caught on something. Under those circumstances, either the mooring line eventually breaks or the line must be cut and only part of the XMOOR salvaged.

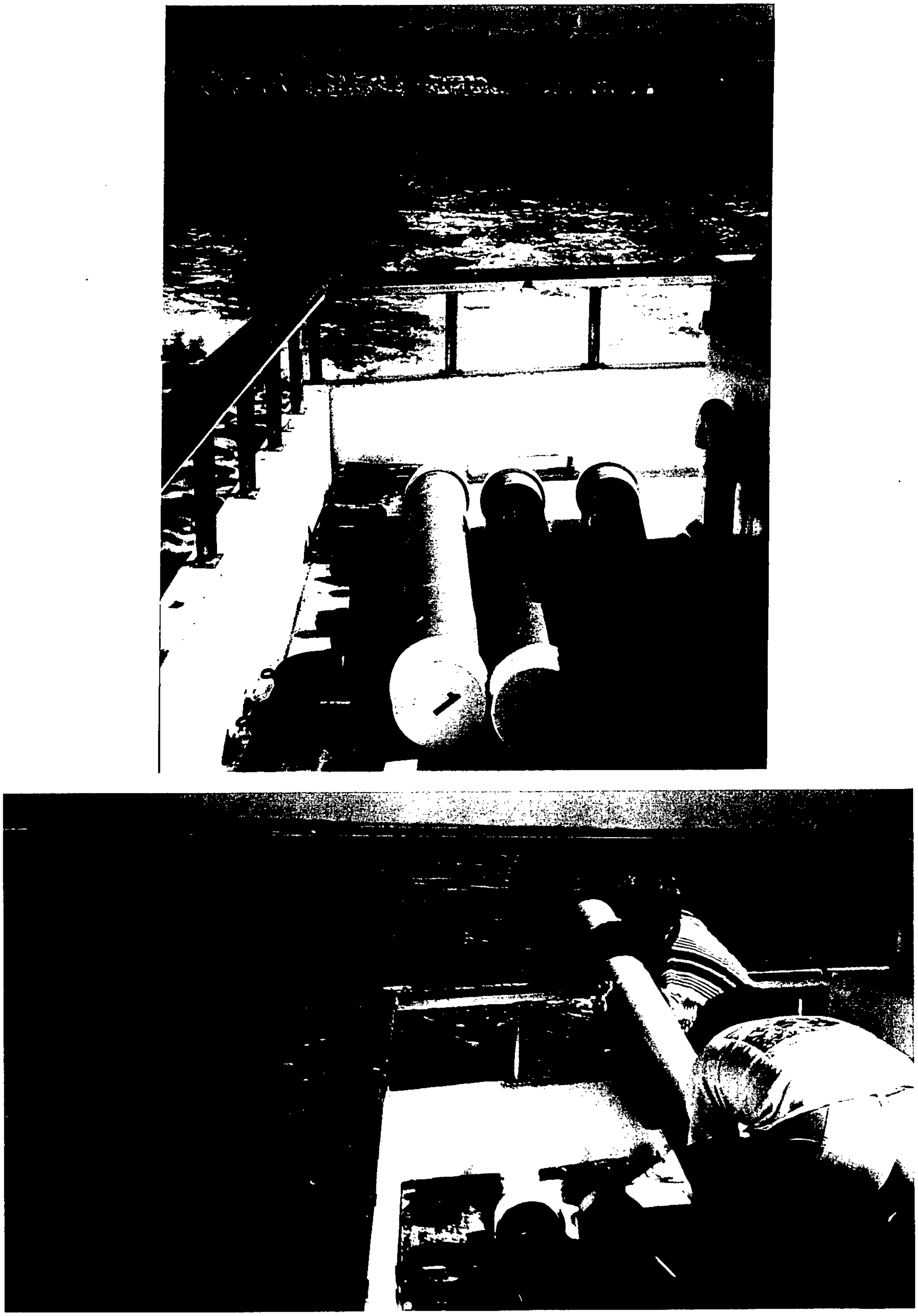

Fig. 10 — A technique for shipping and deploying XMOORs is to enclose them in sections of 8 in. (20 cm) PVC pipe, each with one end permanently capped and the other with a removable cap. For deployment, one cap is removed and two people lift the tube and tip the XMOOR out over the side into the water.

7.0 TEST RESULTS

Several partial and full tests of the XMOOR system have taken place. The general approach for self-deployment has proven reliable except in one case where deteriorated tablets in the actuator caps led to slow and incomplete firing of the gas canisters. Deployments have been successfully achieved in water from about 14 to over 80 m depth. One instance when too much binder was used to coat the thermistor string/strength member coils verified that the XMOOR will indeed become a drifting buoy if the anchor canister does not hit bottom. At-sea tests for a total of 94 d have shown the urethane-coated nylon of the surface buoy to be surprisingly tough and resistant to abrasion, and buoys inflated with N_2 have stayed fully inflated for over 4 mo of combined at-sea and on-land time. Methods used to connect the midwater puck to the strength member were initially problematic due to bending and abrasion. The attachment method was modified by use of a separate bridle that removed the tension from the mooring line where it passes through the puck. The very small glass bead thermistors in the thermistor strings proved susceptible to damage, and future strings will be constructed with larger but more durable epoxy-coated thermistors. Intermittent problems with the inductive telemetry, which we never were able to reliably diagnose and solve, led us to substitute a return wire for the inductive return path rather than using seawater, and this worked without incident for a number of deployments in both fresh and salt water.

Deployments in water 40–80 m deep with surface currents estimated at 50–100 cm/s (1–2 kt) performed satisfactorily; however, in one instance when tidal action and currents were very low and the mooring was quite slack, the mooring line snagged on the bottom. It may indeed be the case that the design condition hardest to engineer is that of a very slack moor rather than the conditions of maximum depth and current. The XMOOR proved easy to deploy and retrieve except in one instance when the anchor apparently snagged on something. Brute force eventually freed the anchor with no apparent damage to any of the connections or the thermistor string.

In Jan–Feb 1997, an approximate 3-wk deployment was conducted in the very shallow (about 2 m) waters of the Long Beach, MS, yacht harbor. XMOOR data were compared with air temperature and barometric pressure from an offshore National Data Buoy Center 3-m discus buoy and water temperature values from a few hand-deployed CTD casts. The results are shown in Fig. 11. The buoy, ID# 42007, is about 18 nmi (33 km) from the yacht harbor and in the waters of the Mississippi Sound. XMOOR and buoy values for barometric pressure were nearly identical and the two traces cannot be distinguished in Fig. 11. The XMOOR air temperature values vary between much greater extremes than the buoy temperatures, but this is to be expected given the different locations of the two instruments. While the two air temperature traces are not identical in Fig. 11, the general trends are the same and the results are quite acceptable.

The XMOOR and CTD values compare very well in Fig. 11. Sea surface temperature came from sensors on the surface canister (as did air temperature and barometric pressure). The panel labeled "near-bottom temperature" came from the first thermistor on the thermistor string. As they should (because they were coiled up close to the first thermistor), the other seven functional thermistors on the 25-m string tracked this thermistor to within a few tenths of a degree.

A complete testing and improvement program for XMOOR was precluded because of early funding termination. As a result, we cannot claim that we were able to achieve all of our design goals with the instrument. However, enough testing was conducted for us to conclude that XMOOR is a successful prototype system that shows great promise for further development.

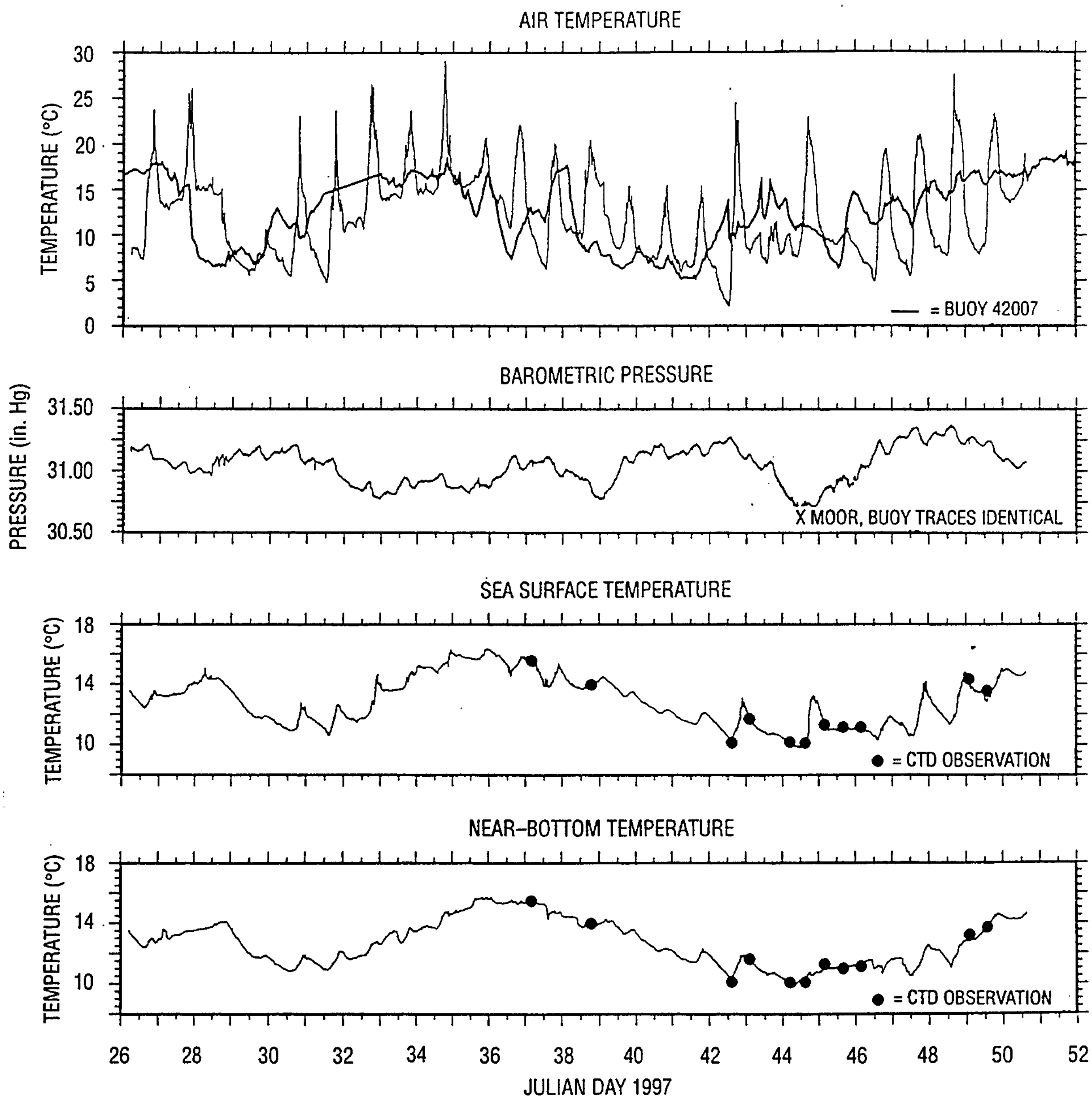

Fig. 11 — Results from 3-wk XMOOR deployment in Long Beach, MS, yacht harbor during Jan–Feb 1997. XMOOR data are compared with air temperature and barometric pressure values from National Data Buoy Center buoy #42007 (dark traces) and water temperature with hand-deployed CTD casts (dark circles). Barometric pressure traces are indistinguishable on this plot.

8.0 SUMMARY

A compact, depth-adaptive and self-deploying coastal oceanographic mooring system has been developed by NRL and WHOI. The prototype surface sensor suite has been barometric pressure and air temperature, SST, and sea surface salinity. Subsurface, one or more thermistor strings give a vertical temperature profile and at up to two depths, small CTD pucks provide conductivity, pressure, and high-accuracy temperature (Table 2). Eight prototype XMOORs have been constructed and limited testing has been performed on all subsystems, as well as on complete units. XMOOR

has achieved most of the goals outlined in the Introduction. However, the present XMOOR is a working proof-of-concept system, and as such has demonstrated both strengths and weaknesses. Design implementations that worked well included the collapsible sleeve antenna, the self-deployment sequence with self-inflating buoy using N_2, the molded meteorological sensor system, ARGOS and spread spectrum radio communications, the data acquisition and control software approach, unspooling of the line and thermistor string from the falling line canister, the depth-adaptive lockup mechanism, and the collapsible anchor.

A number of design implementations did not work as satisfactorily, however. Inductive telemetry adds cost and complexity that may not be warranted in what is intended to be a relatively low-cost system. It would be a good approach for a profiling instrumentation package that moves up and down a mooring line, but for a set of distributed, fixed sensors, more standard approaches are probably cheaper and easier to use. The mini CTD pucks are an innovative solution to acquiring accurate temperature, pressure, and conductivity measurements at selected depths and might find application outside of XMOOR, but they are relatively expensive and take up considerable space in the line canister. Attachment to the mooring line also proved problematic due to the constant stresses experienced in the ocean environment. The ARGOS and spread spectrum radio communications worked as desired, but a larger bandwidth (in the case of ARGOS) and longer range (in the case of the radio) communications technique would be highly desirable. Finally, vandalism is a major problem with instrumentation deployed in shallow, heavily trafficked areas. The inflatable toroid floats high in the water, making it easy to spot for retrieval...and also for vandalism.

Finally, improvements in miniaturization of oceanographic sensors are needed to fully realize the XMOOR potential. Water current profiles, for example, are needed for some applications. One possible approach—though not necessarily an inexpensive one—would be the incorporation into the surface or bottom unit of a miniaturized acoustic Doppler current profiler. Potentially suitable, low-cost systems are presently under development with support from the DoD Small Business Innovative Research (SBIR) Program. Tidal height measurements could be acquired with a bottom-mounted pressure sensor, and with periodic bursts of high-frequency sampling, the pressure measurements could also be used to compute nondirectional wave parameters. Small, relatively inexpensive pressure, conductivity and/or sound speed, and turbidity sensors that could be installed into the same cable as the thermistors and not interfere with the cable's uncoiling would also be useful in many applications.

XMOOR is a working system that achieved many of its initial goals, but full maturation of the concept will come with improved satellite communications systems and a wider array of miniaturized ocean sensors. These are on the near horizon.

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